Inertia and Gravitation as Vacuum Effects – the case for Passive Gravitational Mass

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Abstract. It has previously been shown that there is a connection between the vacuum electromagnetic field, or zero-point electromagnetic field, and the phenomenon of inertia. A general expression was then derived for the vacuum electromagnetic contribution to the inertial mass of an object. Similar contributions are to be expected from the other vacuum field components. Here we show that the case for inertial mass can indeed be extended to passive gravitational mass. As a byproduct of this we also get Newton's law of universal gravitation. It is furthermore shown why these results are consistent with gravitational theories of the metric kind and in particular with General Relativity. The extension to active gravitational mass, namely, solving the problem of why mass creates a gravitational field, i.e., why it "bends" or changes the curvature of spacetime, remains unsolved.
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1. INTRODUCTION

There are three different manifestations of what we ordinarily call mass. This has led to what in principle could be three different parameters, but that our adherence to the unity of Physics forces into a single one. These different mass parameters are inertial mass, passive gravitational mass, and active gravitational mass, which by the way are thoroughly discussed in a recent book of Jammer [1]. In previous work [2] we have been dealing with inertial mass. Here we consider passive gravitational mass.

Assuming the Einstein local Lorentz-invariance principle, we will show that a previously derived expression for the inertial mass contribution, mi, from the electromagnetic vacuum field is equal to the corresponding contribution, mg, to the passive gravitational mass. Thus, within the electromagnetic vacuum viewpoint proposed in Ref. [2], the Newton's weak equivalence principle, mi = mg, ensues in a straightforward manner. It can also be shown, by means of simple arguments from symmetry and from potential theory plus time-revered natural physical assumptions, that because of geometrical reasons the Newtonian gravitational force law necessarily follows in the weak field limit. So, the vacuum electromagnetic field approach to inertia of Ref. [2], when extended to gravity, yields Newton's gravitation. This analysis however does not pin down the exact form of the gravitational theory that is required, but only that it should be a theory of the metric type, i.e., a theory like Einstein's General Relativity that curves spacetime. Very importantly, however, this present development shows that our previous vacuum inertial mass analysis of Ref. [2] is consistent with General Relativity. Pending remains extension of these analyses to other components of the vacuum (strong, weak vacua).

That there is a contribution to inertial mass from the electromagnetic quantum vacuum has been shown by means of a closely detailed argument [2,3], (see also Ref. 4) that uses some of the techniques developed in a semiclassical theoretical technique called Stochastic Electrodynamics (SED) [5]. However, according to the weak equivalence principle (WEP) of Newton and Galileo, inertial mass, m_i, is equal, modulo a constant that with a proper selection of units is conventionally set to unity, to passive gravitational mass, m_g. So it is not far-fetched to expect that exactly the same vacuum contribution that appears for inertial mass should also appear for passive gravitational mass. This novel feature, $m_g = m_i$, never shown before, is what we first show in Section 2, by means of a straightforward argument that requires only natural and ordinary physical assumptions of wide acceptance in theoretical physics. In Section 3 the consistency of this argument with so-called metric theories of gravity, i.e., those theories characterized by space-time bending, is exhibited. Our argument will not allow us, however, to be able to tell which one of those

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theories is the one consistent with our work. As Einstein's General Relativity (GR) is par excellence a metric theory of gravity, our argument definitely shows that our previous work [2,3] and the present simple derivation are all exactly consistent with the standard version of GR. Next, in Section 4, taking advantage of certain symmetries, standard potential theory allows us to show that, because of geometrical reasons, in the weak field limit, that is the only case really considered here, the Newtonian gravitational inverse-square-force-with-distance also follows. In Section 5 we discuss a thermodynamics aspect of the present derivation: An apparent paradox is resolved by means of a simple argument. A brief discussion on the nature of the gravitational field is also included (Section 6) but as it also happens in GR and in most related standard theoretical analyses, the ultimate and fundamental reason why matter has the ability to bend space-time can be neither properly addressed, nor satisfactorily elucidated from our present development. Section 7 presents the conclusions.

2. VACUUM ELECTROMAGNETIC CONTRIBUTION TO PASSIVE GRAVITATIONAL MASS

2.1 Einstein Local Inertial Frames and Rindler's Noninertial Frame

Consider a fixed in space, relatively large and massive object W, that, for concreteness, we assume as fairly condensed and with a spherically symmetrical mass distribution of radius a. At a large distance, r, from the center of W, (r >> a), there is a much smaller material object w, that we can consider, for most purposes, to be an almost punctual test body and that again, for the purposes of our discussion, we can assimilate to a classical point particle. A constant force f is exerted by an external agent that prevents the small body w from falling into the gravitational potential of W and maintains it at a fixed point in space a distance r from the center of W. Experience has told us that if w were to let fall freely towards W, at the point in time when the force f was removed and w initiated its drop towards W, it would instantaneously start to move with an acceleration of magnitude g. Next we consider a freely falling local inertial frame I*, (in the usual sense given to such local kind of frame [6]) that instantaneously is at rest with respect to the particle. At a particle proper time τ, that we select to be $\tau = 0$, the particle is instantaneously at rest at the point (c2/g,0,0) of the I* frame. The x-axis of that frame goes in the direction from W to w and as the frame I* is freely falling towards W, at $\tau = 0$, the particle appears accelerated in I* in the x-direction and with an acceleration.

$$\mathbf{g}_p = \hat{\boldsymbol{x}}\, g.$$

Thus the particle is clearly performing a uniformly accelerated motion with a constant proper acceleration $\mathbf{g}_p$ as contemplated from any neighboring instantaneously commoving (local) inertial frame. In this respect we introduce an infinite collection of (local) inertial frames I_τ, with axes parallel to those of I_* and with a common x-axis which is that of I_*. Let the particle be instantaneously at rest and commoving with the frame I_τ at particle proper time τ. So the τ parameter, which represents the particle proper time, also serves to parametrize this infinite collection of (local) inertial frames. Clearly then, I_* is the member of the collection with $\tau = 0$, so that $I_* = I_{\tau=0}$. For uniformity and at the time point of coincidence with a given I_τ, we locate the particle at the $(c^2/g,0,0)$ space point of the I_τ frame. We select also the time t_τ in each one of the (local) inertial frames I_τ to be such that $t_\tau = 0$ at the moment of coincidence when the particle is instantaneously at rest in I_τ and at the above mentioned $(c^2/g,0,0)$ space point of I_τ. Clearly as $I_{\tau=0} = I_*$ then $t_* = 0$ when $\tau = 0$. All the frames in the collection are freely falling towards W and when any one of them is instantaneously at rest with the particle, it is instantaneously falling with acceleration

$$\mathbf{g} = -\,\mathbf{g}_p = -\,\hat{\boldsymbol{x}}\, g$$

with respect to the particle and in the direction of W. It is not difficult to realize that the particle appears in those frames as performing a hyperbolic motion with proper particle acceleration $\mathbf{g}_p$.

For convenience we introduce a frame of reference whose x-axis coincides with those of the I_τ frames, including of course I_*, and whose y and z-axes are parallel to those of I_τ and I_*. This frame S stays put with the particle w which is positioned at the $(c^2/g,0,0)$ point of this S frame. For I_* (and for the I_τ) the frame S appears as accelerated with the proper acceleration $\mathbf{g}_p$ of its point $(c^2/g,0,0)$. We will assume that the frame S is rigid. If so, the accelerations of points of S sufficiently separated from the particle point $(c^2/g,0,0)$ are not going to remain the same. This will not be of much concern because as explained below, we will only need to consider in S, and in the freely falling inertial frames I_* and I_τ, points within a sufficiently small neighborhood of the $(c^2/g, 0,0)$ point of each frame. It can be seen that the present collection of frames, I_*, I_τ, and S, exactly correspond to the set of frames introduced in Ref. [2]. The only differences are, first, that now the frames are all local, in the sense that they are only well defined for regions in the neighborhood of their respective (c^2/g,0,0) space points, and second, that now I_* and the I_τ frames are all considered to be freely falling towards W and the S frame is fixed with respect to W. Similarly to Ref. [2], the S frame may again be considered to be, from the viewpoint of the I_*, a *Rindler noninertial frame*. The laboratory frame I_* we now call the *Einstein lift frame,* as now the "laboratory" is local and freely falling.

2.2 The Assumptions

In this report we are going to extend our previous argument of Ref. [2], which worked nicely for inertia, to the case of passive gravity. So, naturally, we are going to take for granted and assume all our highly reproducible and closely argued results presented in Ref. [2]. This is our *First Assumption*. In addition there are two more general assumptions that though of widespread acceptance, deserve an explicit comment. But before doing that we recall from Special Relativity the relativity principle (RP). Einstein stated it as, "all inertial frames are totally equivalent for the performance of all physical experiments" [7]. So, in Special Relativity we assume that the laws of physics are identically the same in all Lorentz invariant frames, i.e., in inertial frames mutually moving with respect to each other with uniform velocities. We will come back to this below. Here, however, we cannot assume the RP, because we will also be dealing with gravity. This is a modification that will have to be done to our assumptions of Ref. [2]. We will have to restrict the RP in the form of an extension of it first proposed by Einstein [8].

We proceed then with our *Second Assumption*: The space and time uniformity assumption (UA). It is fairly general but also widely accepted: The laws of physics are always the same timewise and spacewise. Namely, the results of experiments performed under identical conditions are the same in different places in the Universe and at different times. Will [9] states the UA more precisely: "the outcome of any local nongravitational test experiment is independent of where and when in the universe it is performed." The restriction to "local" is explained in the next assumption where we discuss the locality issue. A nongravitational test experiment is one for which self-gravitating effects can be neglected. The experiment should be done in an isolated system sufficiently shielded from any outside perturbing influence.

Next we give our T*hird Assumption*. It is a widely accepted restriction that Einstein imposed, on the infinitely extended Lorentz invariant frames of the RP, in order to be able to pass a restricted version of Special Relativity to General Relativity [8]. Will [9] states it as "the outcome of any local nongravitational test experiment is independent of the velocity of the freely falling apparatus." Here then the RP is restricted to *local* Lorentz invariant freely falling frames, i.e., frames that fall freely in a gravitational field but that are of small enough size and stay in operation for short enough time such that no gravitational inhomogeneities (tidal forces) can be of relevance to the experiments. This assumption is usually called the local Lorentz invariance (LLI) principle [7,9].

For some general purposes the above two general principles may not be satisfactory. For example, in theories where the universal constants change with cosmological time as that of Dirac for the gravitational constant G [10], the UA, as stated here, does not apply. Usually, however, as often done in Cosmology, one may prefer to modify the postulational system one is dealing with in such a way as the UA is not sacrificed. All-in-all the UA is very widely used, though not always explicitly. It is implicitly assumed in most treatises on theoretical physics. The LLI principle is also widely accepted and difficult to avoid. In spite of claims to the contrary by Synge and others [11, 12], we, following the majority of authors on modern gravitational theory, e.g. Ref. [7] and [9] and many others, firmly adopt the LLI principle. There is no question, despite some statements to the contrary [11, 12], that Einstein also firmly adopted it [8] and that he thought it had great heuristic value. Synge's complaint about tidal effects is not of much weight since one can always meaningfully assume small enough spacetime regions without any loss whatsoever of conceptual generality. There are many examples of this kind of coarse graining procedure in theoretical physics, e.g., in condensed matter and in statistical physics the averagings needed to define the charge density ρ or the **D**-field in a dielectric, to name a few. All these lead to meaningful physics.

2.3 Equivalence of Inertial and Passive Gravitational Masses

So far and within the standard theoretical frame of GR and related theories, the equality (or proportionality) of inertial mass to gravitational mass has to be assumed. It remains unexplained. As correctly stated by Rindler [13], "the proportionality of inertial and gravitational mass for different materials is really a very mysterious fact."

However, here we show that within the vacuum approach to inertial mass presented in Ref. [2], such proportionality and equivalence comes out rather naturally.

When the Einstein LLI principle, discussed in Subsection 2.2, is applied to the situation envisaged in Subsection 2.1, because the local I_* and I_τ frames of Subsection 2.1 are inertial with the same laws of physics holding as in all Special Relativity Lorentzian frames, there is a zero-point field (ZPF) that can be associated with each one of then exactly in the same way as was done for the extended I_* and I_τ frames in Ref. [2]. If so, all the arguments that applied to the inertia derivation in Ref. [2] also apply, mutatis mutandis, to the present case. So, as thoroughly shown in Ref. [2], in the present case it should appear to the freely falling inertial observers of the local Lorentz invariant frames, I_* and I_τ, that the body w is uniformly accelerated and that a drag force, as explained in Ref. [2], is present and creates the inertia reaction force that we now view as appearing in w and in the direction of W. In this new situation, the associated nonrelativistic form of the inertia reaction force, as it was for Ref. [2], should be, in the nonrelativistic case:

$$\mathbf{f}^{*zp} = -\, m_i \mathbf{g}_p \,, \tag{1}$$

where $\mathbf{g}_\mathrm{p}$ is the acceleration with which w appears in the local inertial frame I_*. And as far as the coefficient m_i goes, it should be exactly the same m_i as in Ref. [1], namely:

$$m_i = \left[\frac{V_0}{c^2} \int \eta(\omega) \frac{\hbar \omega^3}{2\pi^2 c^3} d\omega \right], \tag{2}$$

where V_0 is a parameter we identify with the proper volume of the particle, c is the speed of light, $\hbar$ is Planck's constant divided by 2π, and the coupling function $\eta(\omega)$, $0 \le \eta(\omega) \le 1$, assigns the relative effectiveness that each ZPF frequency component has in interacting with the accelerated body w and thereby in opposing its acceleration. But now clearly what appears as inertial mass to the observer in the local I_* inertial frame is of course what corresponds to gravitational mass, m_g, and it must be that:

$$m_g = \left[\frac{V_0}{c^2} \int \eta(\omega) \frac{\hbar \omega^3}{2\pi^2 c^3} d\omega \right]. \tag{3}$$

As done in Ref. [2], Appendix B, it can be shown that m_g indeed represents the ZPF energy enclosed within the particle's volume and able to interact with the particle (via the $\eta(\omega)$ coupling function). A more thorough development can also be implemented to show that the force expression of Eq. (1) can be extended to the relativistic case (Ref. [2], Appendix D). But we do not need to write that explicitly for the present paper. Summarizing what we have shown in this Section, is that if a force **f** is applied to the w body to prevent it from falling towards the body W, in the nonrelativistic case, that force is given by:

$$\mathbf{f} = -\, m\mathbf{g}_p = m\mathbf{g} \,, \tag{4}$$

where we have dropped nonessential subscripts and superscripts. The subscripts for the masses m_i and m_g, of Eqs. (2) and (3) above, we may delete as $m_i = m_g \equiv m$.

3. CONSISTENCY WITH GENERAL RELATIVITY

The statement that the inertial mass, m_i, is exactly equal to the gravitational mass, m_g, that we have just shown, constitutes what is called the weak equivalence principle (WEP), whose origin goes back to Newton and Galileo [7,9]. Ohanian and Ruffini [12] in their textbook make it the basis of their development. As explained by Will [9], if the WEP is explicitly assumed together with LLI and UA, one has the Einstein *strong equivalence principle* (SEP). So, clearly our inertial approach [2,3] and its extension to passive gravity done here, is consistent with all theories that are derived from the SEP. The two most well-known examples of those theories are the Brans-Dicke theory and Einstein's GR. There are a few more examples [9] but the last two are the ones with more acceptance and, of course, GR is by far the most widely accepted of the two. All theories that assume the SEP, in addition to the various idiosyncratic assumptions proper of each one of the theories, are called *metric theories* [9]. They are characterized by the fact that they contemplate a "bending" of spacetime associated with the presence of matter. The main consequences of LLI (consequences usually derived by means of Einstein's lift thought experiments), plus the WEP and the UA principle, is that light bends in the presence of matter and that there is a gravitational Doppler shift [14].

Hence our approach of Ref. [2] and the development here, also requires that light bends in the presence of gravitational fields. Actually this fact implies that the gravitational field can be identified with the spacetime geometrical change associated with this bending. More on this will be discussed below.

Having established this consistency with metric theories, we must acknowledge however, that we still need to show that our approach yields passive gravity, at least in its most elementary form. Namely, that it yields simple well-known results as Newton's gravitational law. This is the subject of the next Section.

4. DERIVATION OF NEWTON'S LAW OF GRAVITATION

4.1 General remarks

Here we show how the simple analysis presented above and its predecessor in Ref. [2], lead inexorably to Newton's gravitational law. As in previous Sections, the small speeds and small fields approximation is assumed which is the case contemplated here and in most of Ref. [2] anyway (except for Ref. [2] Appendix D, where the covariant formulation was developed). However, the idea that the vacuum is ultimately responsible for the gravitational effects that we observe, is not new. It goes back to a proposal by Sakharov [15] based in part on work of Zeldovich [16]. By attempting to connect Hilbert-Einstein's action to the quantum vacuum, Sakharov proposed that gravity was indeed a "metric elasticity of space." An instructive review of Sakharov's views is presented by Misner, Thorne, and Wheeler [17]. A paper by Puthoff [18] gives a detailed account of the various approaches, prior to 1989 that, in one way or another, attempted to develop Sakharov's idea.

4.2 Derivation of Newton's law of gravitation

From Eq. (4) and its surrounding lines, it is clear that the **g** field generated by the spherically symmetric condensed body *W* is *central*, i.e., centrally distributed with spherical symmetry around *W*. It thus has to be radial, with its vectorial direction parallel to the corresponding radius vector that comes from *W* where the origin of coordinates is located. So it is in the direction of $-\mathbf{r}$ and depends only on the *r* coordinate.

The field is clearly generated by mass. The mass *M* of *W* is the field's negative source (or sink). Physically this implies that the field lines of **g** only can be discontinuous or broken where mass is present. Hence the field lines cannot be generated (or destroyed) in free space. More on this we argue below, but we also need what follows. As **g** is also the force on the unit mass, we know that **g**, because it is a force, behaves vectorially. Namely, it must be that if two masses M_1 and M_2, each one independently on its own generates the fields $\mathbf{g}_1$ and $\mathbf{g}_2$ respectively, when the two masses M_1 and M_2 are placed at nearby points in space, the resulting field **g** due to the action of the two masses, is going to be the simple additive superposition of the field of M_1 and the field of M_2, namely that:

$$\mathbf{g} = \mathbf{g}_1 + \mathbf{g}_2 \tag{5}$$

It can also easily be argued that if we scale the mass *M* of *W* by a factor α, $\alpha > 0$, namely αM, then the resulting **g** must be of the form $\alpha\mathbf{g}$. So the field **g** obeys full linear superposition. It is also clear from the above and the argument of Section 2 that the field **g** generated by *W* is unbounded, it indefinitely extends to infinity.

The argument just given naturally leads to the idea that the lines of **g** (in the sense of Faraday) obey the continuity property, a time-honored idea that goes back to Gauss and perhaps even back to Newton [19]! Namely, if mass is not present inside the volume enclosed by a closed surface *S*, we must have that:

$$0 = \oint_{S(V)} \mathbf{g} \cdot \mathbf{n}\, dS = \int_V \nabla \cdot \mathbf{g}\, dV, \tag{6}$$

where the second equality follows from Gauss' divergence theorem. As *V* is arbitrary we then have that:

$$\nabla \bullet \mathbf{g} = 0, \qquad r > a, \tag{7}$$

where a is the radius of the W body. And as $\mathbf{g}$ is radial, we obtain from solving this differential equation that:

$$\mathbf{g} \sim \hat{\boldsymbol{r}} \frac{1}{r^2} \tag{8}$$

The field $\mathbf{g}$ is also proportional to the mass M that originates it. We can then see that $\mathbf{g}$ has to be of the form:

$$\mathbf{g} = \hat{\boldsymbol{r}} \frac{GM}{r^2}, \tag{9}$$

where G is just a proportionality constant and from Eq. (4) and recalling that $\mathbf{g}_p = -\mathbf{g}$ we have that:

$$\mathbf{f} = -\hat{\boldsymbol{r}} \frac{GMm}{r^2}, \tag{10}$$

which is Newton's law of universal gravitation.

5. A THERMODYNAMICS PARADOX?

An apparent paradoxical situation arises when one considers that in the analysis of Section 2 we found that for the observers in the freely falling LLI frames I_* and I_τ the small massive object w appears as accelerated and therefore, according to the reasoning introduced in Ref. [2], under a net Poynting vector that seemingly pushes w in the direction of W. If this same analysis is performed along any other radial direction away from the origin at W, one obviously finds again exactly the same centrally directed Poynting vector. This would seem to imply that W should generate a very odd thermodynamic situation around itself with ZPF energy coming towards W from all directions in space.

This conclusion though globally valid cannot be rigorously substantiated. Let us locate w not far away from the surface of W, that we may identify with the Earth, and for simplicity assume W is perfectly spherical of radius a and of strictly homogeneous density. Let the test body w be now very much smaller than W and again assume it is kept from falling towards W by the supporting force $\mathbf{f}$ as in Eq. (4).

We only need to realize two facts. The Poynting vector that appears acting on w is only consistent for a given freely falling LLI frame or at most for the family of frames I_τ, where $I_{\tau=0} = I_*$, along the particular straight radius vector going from W to w.

For example, consider a small body w' and associated set of frames I'_τ and I'_* falling freely towards W and defined exactly the same as I_τ and I_* were defined in section 3, but whose radii vectors of free fall towards W are along the widely different direction that goes from W to w'. As occurs with the observers of unprimed frame S, observers in the primed frame S' also claim there is a ZPF Poynting vector along their radial direction or x'-axis and hitting the body w' in the direction pointing towards W. But for the primed frames observers the unprimed frames direction of the fall towards W that goes from w to W, is not a direction of any net Poynting vector. The reverse conclusion also holds. For the unprimed frames there is not a net Poynting vector along the radial direction (x'-axis) of the primed frames.

Therefore this shows that those Poynting vectors appear as such only for a selectively restricted class of LLI frames. The only way we could produce a consistent conclusion about this odd thermodynamic situation would be if we could find a single freely falling LLI frame from which we could simultaneously make a consistent conclusion about the nature of all such Poynting vectors. Fortunately there precisely exists such a frame.

Consider the sphere of the Earth. As one goes more and more deeply inside, the $\mathbf{g}$ field decreases more and more. Freely falling frames found more and more inside the Earth fall with smaller and smaller accelerations, and at the exact center of the Earth the $\mathbf{g}$ acceleration is exactly zero. We can actually quantify this in full precision since we have already discovered that the gravitational force goes as $1/r^2$. To show these details is a simple exercise in elementary physics.

There is one single freely falling LLI frame that is a member of all radial families of free falling frames and that is the LLI frame exactly at the center of the Earth that we shall call *C*. From that frame *C* we can observe and make consistent conclusions about all the Poynting vectors along all possible radial directions towards the center of *W*. But surprisingly *C* is not only freely falling with exactly zero acceleration but also, as it started from rest, it has always been at rest at the center of the Earth.

Then for this frame *C* at the center of the Earth, we can consistently look in all possible radial directions. Consider the typical one that goes from the center of *W* to *w*. As *w* is at a fixed distance from the center of *W* and thus is fixed, has zero acceleration, and is not moving with respect to an observer in *C*, there cannot be any Poynting vector due to the ZPF of *C* impinging on *w*, because *w* does not appear accelerated as viewed from *C*. So, the Poynting vector disappears along that particular radial direction. Therefore by symmetry, it disappears along all radial directions from the center of *W* and the paradox is resolved: The only single frame from which a consistent conclusion referring to all Poynting vectors along all possible radial directions from the center of *W* can be drawn, yields that such Poynting vectors exactly vanish! The observer in *C* does not infer any net radiation influx towards *W* from any direction in space. This enormously weakens the strength of the thermodynamics objection.

In spite of this let us assume, for the sake of the discussion and because of its global validity, there was such an inflow of energy from the falling vacuum towards *W*: Observe then that any massive body, *W*, as it produces a surrounding gravitational field will present the same falling vacuum phenomenon we alluded to in the previous paragraph. Such falling vacuum we assume may imply some inner inflow of energy towards the body *W*. If so, that energy should be balanced by an equal outward outflow of energy. There is a source of that outflow: The electromagnetically interacting charged particles of the massive body are seen as uniformly accelerated from the falling LLI Einstein frames. Therefore they should radiate energy outwards! We conjecture that this outward flow should balance the falling energy flow surmised above. We plan to explore this conjuncture in more detail.

6. DISCUSSION

We would like first to elucidate something about the nature of the gravitational field. In the low fields and low velocities version, or Newtonian limit, we have seen above that gravity manifests itself as the attractive force per unit mass, **g**, of Eq. (4) that pulls any massive test body present at a given point in space towards the body *W* that originates the field. As we assumed the Einstein LLI principle and from this derived the WEP, this, together with the very natural UA, or invariance in the laws of physics throughout universal spacetime, lead us to the Einstein SEP which necessarily implies the spacetime bending representation of the generalized gravitational field [9].

A simple thought experiment (Einstein's lift) immediately shows that light rays propagate along geodesics, and more specifically along null geodesics. The spacetime bending is dramatically evident when a light ray goes from one side to the other of the freely falling elevator. For the observer attached to the elevator's frame that indeed acts as a LLI frame, the light ray propagates in a straight line from one side to the other of the elevator. But for the stationary observer that sees the elevator falling with acceleration **g**, the light ray bends along a path that locally is seen as a parabolic curve. Undoubtedly the most natural explanation for the stationary observer is that spacetime bends and therefore, the association that this bending is a manifestation of the gravitational field of W, or rather that this bending of spacetime *is* what constitutes the gravitational field itself [20].

Starting from the above fact taken as a given, the various metric theories proceed from there to formulate their equations. In the version of Brans and Dicke a scalar-tensor field is assumed. In Einstein's General Relativity only a tensor field is proposed. Following this maximally simplistic proposal, and guided by general considerations of general covariance (the need of arbitrary coordinates and tensor laws) Einstein was led to his field equations in the presence of matter. And then GR naturally unfolded [7, 9, 11, 12, 20].

We have shown here that our inertia proposal of Ref. [2] leads us, when constrained by the LLI principle, to the metric theories and therefore that this proposal is consistent with those theories and in particular with Einstein's GR. In addition, there is the following interesting feature in our proposal.

From our analysis in Ref. [2], and in particular in Appendix B of Ref. [2], it was made clear that as far as the vacuum electromagnetic ZPF contribution to inertia is concerned, the mass of the object, m, could be viewed as the energy in the equivalent vacuum electromagnetic ZPF captured within the structure of the object and that readily interacted with the object. It was surprising how this view matched perfectly with the complementary view thoroughly exposed in other parts of the paper [2] that presented inertia as the result of a vacuum reaction effect, a kind of drag force exerted by the vacuum field on accelerated objects. Quantitatively both approaches lead to exactly the same inertial mass and moreover they were partly complementary. Both viewpoints were needed. One could not exist without the other, they were like two sides of the same coin.

The idea that the electromagnetic ZPF background freely falls in a gravitational field has been essential throughout the development of this work. Very recently we have found support in a related idea in the literature. When studying the problem of radiation from an accelerated charge in a gravitational field Harpaz and Soker [21] proposed that the electric field from a charge, irrespective of the state of motion of the charge, falls freely when submitted to the action of a gravitational field. We think that their argument is conclusive, as it presents a much more clear and consistent understanding of radiation reaction that exactly fits Einstein's SEP. It is better than many prior proposals and it both uses previous developments and gives an overall clear view of those developments.

The question is now why massive objects, when freely falling, also follow geodesic paths. The temptative view suggested here is that, as a massive body (according to our analysis of Ref. [2], Appendix B) has a mass that is made of the vacuum fields and at least part of it from vacuum electromagnetic energy contained within its structure and that readily interacts with such structure, it is no surprise that geodesics are its natural path of motion during free fall. Electromagnetic radiation has been shown by Einstein to follow precisely geodesic paths. The only difference now is that, as the radiation stays within the accelerated body structure and is contained within that structure and thereby as a whole moves subrelativistically, these geodesics are just time-like and not null ones as in the case of freely propagating light rays.

Neither our approach nor the conventional presentations of general relativity can offer a physical explanation for the mechanism generating the bending of spacetime as related to energy density. Misner, Thorne and Wheeler [17] present six different proposed explanations. The sixth one is that already mentioned (due to Sakharov [15,16]), which starts from general vacuum considerations. As our approach starts also from vacuum considerations, it naturally fits better the concept of this conjecture of Sakharov [15] and Zeldovich [16] than the other proposals, but it is not inconsistent with any of them. In particular the strictly formal proposal of Hilbert [17] that introduces the so-called Einstein-Hilbert action, is also at the origin of the Sakharov proposal.

7. CONCLUSION

We would like to state as a summary, the highlights of this paper:

a) *Derivation of the identity of inertial mass with passive gravitational mass, $m_i = m_g$. (Weak Equivalence Principle)*

It has been shown that the approach of Ref. [2] obtains this particular feature that, so far and as we know, had never been previously justified.

b) *Realize the fitting of the inertia approach of Ref. [2] to the fundamental assumptions of Einstein's GR.*

We have already commented above, in particular in Section 6, on this interesting feature presented in Section 3 that puts the vacuum inertia approach of Ref. [2] within the mainstream of contemporary gravitational theories, specifically within theories of the metric type and in particular in rapport to Einstein's GR.

c) *Derivation of Newton's gravitational law from general principles plus the vacuum inertia approach of Ref. [2].*

By means of a simple argument based on potential theory we obtain in a natural way Newton's inverse square force with distance from the vacuum approach to inertia of Ref. [2].

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REFERENCES

1. For a very detailed and well-organized examination of the concept of mass see Max Jammer, "Concepts of Mass in Contemporary Physics and Philosophy," (Princeton University Press, Princeton, N.J., 2000).
2. Rueda, A., and Haisch, B.: *Found. Physics*. **28**, 1057 -1108 (1998). For a review of the main concepts of this paper see "A vacuum inertia reaction force" by A. Rueda and B. Haisch in *Computing Anticipatory Systems* CASYS 2000 – Fourth International Conference, D. M. Dubois, editor, *AIP Conference Proceedings* Vol. 573, pp. 89-97 (Melville, NY, 2001).
3. Rueda, A., and Haisch, B.: *Phys. Lett*. **A 240**, 115 - 126 (1998). This is a summary of the main results of Ref. [2].
4. Haisch, B., Rueda, A., and Puthoff, H.E.: *Phys. Rev* **A 48**, 678 (1994). This was the first work in a search for the origin of inertia in the quantum vacuum. The fact that it dealt with a too concrete model and that the development was mathematically involved lead to the necessity of showing that if this proposal for inertia is true, there must exist an asymmetry in the electromagnetic vacuum when seen from the standpoint of an accelerated observer. This last was the work reported in Refs. [2] and [3] above.
5. De La Peña, L., and Cetto, A.M.: *The Quantum Dice – An introduction to Stochastic Electrodynamics*. (Kluwer Acad. Publ., Fundamental Theories of Physics, Dordrecht, Holland, 1996). This book was reviewed by Cole, D.C., and Rueda, A.: *Found. Phys*. **26**, 1559 - 1562 (1996).
6. Will, C.W.: *Theory and Experiment in Gravitational Physics* (Cambridge University Press, Cambridge, 1993), p. 22.
7. Rindler, W.: *Essential Relativity – Special, General and Cosmological* (Springer Verlag, Heidelberg, 1977), p. 7.
8. Einstein, A.: *Ann Phys*. **35**, 898 (1911). For a translation see Kilminster, C.W.: *General Theory of Relativity* (Pergamon, Oxford, 1973), pp. 129-139.
9. Ref. [6] pp. 22-24
10. See, e.g., Dirac, P.A.M.: *Directions in Physics* (Wiley, New York, 1978), in particular Section 5, "Cosmology and the gravitational constant," p. 71 ff.
11. Synge, J.L.: *Relativity, The General Theory* (North Holland P.C., Amsterdam, 1971) pp. ix-x.
12. See also Ohanian, H.C., And Ruffini, R.: *Gravitation and Spacetime* (Norton, New York, 1994), pp. 53-54.
13. Ref. [7] p.17.
14. For a detailed discussion of this see Ref. [7], section 1.21, pp. 20-22.
15. Sakharov, A.D.: *Doklady Akad. Nauk S.S.S.R.* **177**, 70-71 (1967) (English translation in *Sov. Phys. Doklady* **12**, 1040-1041 (1968)).
16. Zeldovich, Yu, B.: *Zh. Eksp. & Teor. Fiz. Pis 'ma* **6**, 883-884 (1967) (English translation in *Sov. Phys. – JETP lett*. **6**, 316-317 (1967)).
17. Misner, C. W., Thorne, K.S., and Wheeler, J.A.: *Gravitation* (Freeman, New York, 1971), pp. 426-428.
18. Puthoff, H.E.: *Phys. Rev*. **A 39**, 2333 (1989).
19. Our arguments may partially be based on potential theory, see, e.g., Kellog, O.D.: *Foundations of Potential Theory* (Dover, New York, 1953), pp. 34-39, in particular see Ex. 3, p. 37.
20. See. e.g., Wald, R.M.: *General Relativity* (Univ. of Chicago Press, Chicago, 1984), p. 67; and, for a popularizing account see, Wald, R.M.: *Space, Time and Gravity Second Edition* (Univ. of Chicago Press, Chicago, 1992), Ch. 3 and in particular pp. 33-34.
21. See, e.g., Harpaz, A. and Soker, N., Gen. Rel. Grav. 30, 1217 (1998); Harpaz, A. and Soker, N., in *Proceedings of the 4th Freedman Int. Seminar on Gravitation and Cosmology*, editors. Yu, N., Garedin et al. (Friedman Lab Pub., St. Petersburg, 1999); and Harpaz, A. and Soker, N., arXiv:physics/9910019 vi (13 Oct., 1999). These also provide extensive references to previous relevant work on the radiation reaction problem.